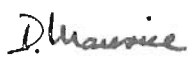


RESEARCH DEPARTMENT

3 × 3 MATRICES FOR USE WITH PLUMBICON COLOUR CAMERAS USING THREE TUBES

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SUMMARY

This report describes the latest developments in the derivation of the coefficients of $[3 \times 3]$ linear matrices for use with the three-plumbicon type of colour television camera. Values are recommended which are equally applicable for both natural daylight and indoor (tungsten) illumination.

1. INTRODUCTION

Two previous reports,^{1,2} have given a detailed account of the methods used to calculate the optimum values of a $[3 \times 3]$ matrix designed to modify the effective colour analysis of a three-tube colour television camera. The starting point of the first report¹ was the optical analysis characteristics used in one commercially available colour camera and the objective was the determination of the best numerical values for a $[3 \times 3]$ matrix for the purpose of minimizing the colour and luminance errors. The second report² was of a more general nature in that no particular optical analysis was assumed; in this case the optimization included a determination of both the optical transmission characteristics and the elements of the $[3 \times 3]$ matrix.

The purpose of the present report is to bring the account up to date in respect of the given transmission characteristics of a particular three-plumbicon colour camera³, and in respect of changes made in the display phosphors.

The previous reports^{1,2} were based on the use of NTSC phosphors and although the manner of calculating for use with other phosphors was indicated*, no reference was made to the set of phosphors currently in use. These are the 'sulphide' blue and green and the rare-earth red; they are specified in Section 4.

2. THEORETICAL CONSIDERATIONS

The elements of a $[3 \times 3]$ matrix depend upon the following parameters:-

- (1) The optical analysis characteristics of the

camera as determined primarily by the colour-splitting system and the tubes.

- (2) The phosphors used in the display tube.
- (3) The white point of the display tube.
- (4) The test colours.
- (5) The illuminant used (usually either tungsten at 3000°K or daylight).
- (6) The criterion function used in the optimization programme.

The use of a $[3 \times 3]$ matrix with a colour camera enables the negative lobes of the ideal analysis curves to be partially realized. If a precise match with the ideal curves were possible, no optimization procedure would be required. With only three receptors, this is not possible if high optical efficiency is simultaneously required.

The precise shape of the full analysis curves is dependent upon the display primaries, which have little effect on the major positive lobes of the analysis curves, but do influence the subsidiary lobes considerably. Since the proposed purpose of the matrix is to supply the subsidiary negative and positive lobes it is very important that it should be designed for the display primaries to be used. A matrix can impair the colour rendering if it is used with primaries other than those for which it was designed.

Because there have been slight changes in colour analysis of the three-plumbicon camera and significant changes in the phosphors employed in display tubes, it is necessary to re-determine the matrix elements.

* Section 3 page 6 of reference 2.

3. CHOICE OF TEST COLOURS

The sets of test colours formerly used^{1,2} did not include flesh tones on the grounds that if both saturated colours and pastel shades covering all the principal hues were included, then the reproduction of flesh colour would almost certainly be good. Although this is probably true, it is now felt that good reproduction of flesh tone is so important that test colours should specifically include several flesh tones. Seven flesh tones have in fact been chosen based upon spectral reflectance curves quoted by MacAdam⁴. The remaining test colours include two grasses, eight highly saturated colours as used in the BBC colour test box for assessing colour cameras and eight colours of about half the saturation of the BBC test-box colours. Table 1 lists the chromaticity co-ordinates of the colours in Illuminant C.

4. CHOICE OF DISPLAY PHOSPHORS AND WHITE POINT

The phosphors used in display tubes have undergone several changes since the original set recommended by the F.C.C.⁵ The present indications are that colour tubes are being made and will continue to be made for some time using the 'sulphide' green and blue phosphors and the 'rare-earth' red. Table 2 gives the chromaticity co-ordinates chosen to represent these phosphors. The figures quoted are the mean of values obtained from direct measurement using a photo-electric tristimulus colorimeter⁶ and the values given by the manufacturers.

The white point has been taken in accordance with the original F.C.C. recommendation (Illuminant C) although it would be preferable to use the recently published Illuminant D₉₅₀₀. For the present purposes, there is little difference between the two illuminants. It is not considered desirable to choose a white point with a colour temperature in excess of 6500°K; the best value probably lies between 5000°K and 6500°K.⁷

5. CHOICE OF 'CRITERION FUNCTION'

The computer programme used to determine the optimum values is a general one and may be described broadly in the following manner. A 'criterion function' has to be defined at the outset and this describes the difference between the desired result and the result achieved at any stage of the working. The programme then calculates the change in the value of this function upon making increments (of appropriate sign) to each of the independent values

(six variables in the present case). From this calculation it chooses a combination of variables to give the maximum slope in the sense of reducing the error. A minimum point is found by quadratic (or, if necessary, cubic) interpolation or limited extrapolation. With the new set of values of the independent variables the process is repeated until no further improvement is possible, i.e. a minimum is reached. At this stage the step size (size of increment) is divided by twenty and the minimization of the error function starts again.

In the present calculation the 'criterion function' is the mean colour error $\bar{n}$ defined as follows:

Let $u_{10} \ v_{10} \ L_{10}, u_{20} \ v_{20} \ L_{20}, \dots, u_{p0} \ v_{p0} \ L_{p0} \dots$

represent the chromaticity co-ordinates (on the 1960 CIE-UCS diagram) and luminance factors of the test colours in Illuminant C and let

$$u_{1r} \ v_{1r} \ L_{1r}, u_{2r} \ v_{2r} \ L_{2r}, \dots, u_{pr} \ v_{pr} \ L_{pr} \dots$$

represent the reproductions by the television system (i.e. camera plus linear matrix plus signal processing units plus colour monitor in the simplest case).

The chromaticity error of the p th colour is defined by

$$n_{cp} = [(u_{pr} - u_{p0})^2 + (v_{pr} - v_{p0})^2]^{1/2} / 0.00384$$

This is the distance on the ' $u - v$ ' chromaticity diagram divided by the magnitude of one just noticeable difference (jnd) as derived from data given by MacAdam.⁸

The mean chromaticity error is

$$\bar{n}_c = \sum_{p=1}^{25} n_{cp} / 25 \quad (\text{there are 25 test colours in the present example (Table 1)})$$

The luminance error of the p th colour is defined by

$$n_{Lp} = [\log_e L_{pr} - \log_e L_{p0}] / 0.0198$$

The mean luminance error is defined as

$$\bar{n}_L = \sum_{p=1}^{25} |n_{Lp}| / 25$$

The modulus of the luminance error is chosen because positive and negative errors in luminance reproduction do not cancel. Each colour tends to be assessed separately in viewing a composite scene.

$\bar{n}$ is defined by

$$\bar{n} = [\bar{n}_c^2 + \bar{n}_L^2]^{1/2}$$

TABLE 1

*Chromaticity Co-ordinates and Luminance Factors of the
23 Test Colours in Illuminant C*

No.	General Description	Chromaticity Co-ordinates		Luminance Factor <i>L</i>
		<i>u</i>	<i>v</i>	
	Reference White	0.201	0.307	1.000
1	flesh	0.225	0.322	0.441
2	flesh	0.228	0.324	0.394
3	flesh	0.231	0.330	0.337
4	flesh	0.235	0.331	0.213
5	flesh	0.243	0.328	0.121
6	flesh	0.236	0.324	0.331
8	grass	0.185	0.336	0.233
9	ivy leaf	0.184	0.324	0.065
10	saturated blue	0.191	0.149	0.047
11	saturated cyan	0.145	0.268	0.329
12	saturated green	0.101	0.370	0.318
13	saturated yellow	0.214	0.372	0.669
14	saturated orange	0.367	0.363	0.290
15	saturated red	0.448	0.355	0.167
16	saturated magenta	0.368	0.298	0.242
17	saturated magenta	0.310	0.221	0.131
18	desaturated blue	0.195	0.257	0.300
19	desaturated cyan	0.179	0.299	0.566
20	desaturated green	0.181	0.342	0.447
21	desaturated yellow	0.209	0.355	0.597
22	desaturated orange	0.257	0.341	0.461
23	desaturated red	0.324	0.328	0.173
24	desaturated magenta	0.309	0.291	0.179
25	desaturated magenta	0.245	0.265	0.350

TABLE 2

Chromaticity Co-ordinates of Display Phosphors

	Chromaticity Co-ordinates	
	<i>u</i>	<i>v</i>
red	0.482	0.342
green	0.122	0.374
blue	0.180	0.100

It is recognized that these formulae are only very approximate. The error function $\bar{n}$ does not, for instance, include the known cross-coupling between chromaticity and luminance which is formulated in Wyszecki's colour difference formulae.⁹ If the colour rendering is very good (e.g. $\bar{n}$ is 1 to 2 jnd) the precise formula used to express the colour error would appear to be less important since, in the limit, all formulae will agree when colour rendering is perfect (i.e. $\bar{n} = 0$).

Even within the above limitations of formulating $\bar{n}$, other criterion functions could be chosen, e.g. an r.m.s. value of the chromaticity and luminance errors could be used

$$n_{rms} = \left[\sum_{p=1}^{25} n_{cp}^2 + \sum_{p=1}^{25} n_{lp}^2 \right]^{1/2} / 25$$

It is felt that the final result does not depend substantially upon the precise formula for the error although it is possible that the number of iterations of the programme required to produce a minimum may depend on the choice of error formula but this has yet to be established.

6. TYPE OF LIGHTING

When the camera is used with natural outdoor lighting, it is regarded as sufficiently accurate to use Illuminant C as a typical outdoor illumination although considerable variations in the colour temperature of daylight do occur. In this case,

there is no change of white point between the scene itself and the reproduction on a colour monitor, and the formulae given in Section 5 are obviously applicable.

When the camera is used with tungsten or tungsten-halogen lighting, some difficulty arises in the definition of colour rendering. The colour television system effects a change of white point from (approximately) 3000°K to 6500°K and the definition of colour error used in this report is based on the colour which the scene would have if it were illuminated by Illuminant C. Alternatively we can regard the scene as though it were viewed through an ideal colour-temperature-raising filter (3000°K to 6500°K). It is recognized that this is only one of several possible definitions of colour error but it has been used for reasons of simplicity and unambiguity. A definition based on identity of colour appearance under the two adapting conditions might be preferable, but there is a lack of quantitative data on which to base explicit numerical equations.

7. RESULTS

The optimum matrix for use in daylight is:-

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix}_{\text{out}} = \begin{bmatrix} 1.544 & -0.524 & -0.021 \\ 0.023 & 1.041 & -0.064 \\ -0.040 & -0.098 & 1.138 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}_{\text{in}} \quad (1)$$

This gives a mean colour error of 1.905 jnds for the 25 test colours.

The optimum matrix for use with indoor 3000°K illumination is:-

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix}_{\text{out}} = \begin{bmatrix} 1.487 & -0.450 & -0.037 \\ -0.001 & 1.053 & -0.052 \\ -0.038 & -0.154 & 1.192 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}_{\text{in}} \quad (2)$$

This gives a mean colour error of 1.562 jnds for the 25 test colours.

In view of the substantial similarity of the two matrices, a matrix with average values has been chosen for all lighting conditions and it has been verified experimentally that this matrix does give good colour reproduction for both indoor (tungsten) and outdoor (natural) illumination.

The recommended 'universal' matrix is thus:-

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix}_{\text{out}} = \begin{bmatrix} 1.516 & -0.487 & -0.029 \\ 0.011 & 1.047 & -0.058 \\ -0.039 & -0.126 & 1.165 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}_{\text{in}} \quad (3)$$

The matrix operates on unity gamma RGB signals which have been equalized on a white card as viewed by the camera under the relevant lighting conditions.

As an indication of the inaccuracy incurred by using matrix (3) under outdoor conditions where matrix (1) ideally should be used, the mean colour error is increased from 1.905 to 2.063 jnds. This is considered to be a negligible price to pay for the operational convenience of using one matrix only.

8. REFERENCES

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